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THE ETL HYBRID OPTICAL/DIGITAL IMAGE PROCESSOR

by

John R. Benton, Francis Corbett and Richard Tuft

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gray scale and color remapping capabilities of the video processor as well as the digital processing capabilities of the mini-computer. The operator can then try new optical filters and iteratively develop optimum methods of detecting patterns. The goal of this research is to develop automated feature extraction algorithms which will minimize the need for human intervention. This system is currently being assembled at ETL, Fort Belvoir, VA.

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The ETL hybrid optical/digital image processor

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Abstract

An optical-digital processor for generalized image enhancement and filtering has been designed and is now under construction.

The optical subsystem is a two PROM Fourier filter processor. Input imagery is isolated, scaled, and imaged onto the first PROM. This input plane acts like a liquid gate and serves as an incoherent to coherent converter. The image is transformed onto a second PROM which also serves as a filter medium. Filters are written onto the second PROM with a laser scanner in real time.

A solid state CCTV camera records the filtered image which is then digitized and stored in a digital image processor. The operator can then manipulate the filtered image using the gray scale and color remapping capabilities of the video processor as well as the digital processing capabilities of the mini-computer. The operator can then try new optical filters and iteratively develop optimum methods of detecting patterns. The goal of this research is to develop automated feature extraction algorithms which will minimize the need for human intervention. This system is currently being assembled at ETL, Fort Belvoir, VA.

Introduction

The computing power of modern digital computers is awesome until one considers the number of pixels contained in an aerial photograph. Alternatively, coherent optical systems have a large space bandwidth product but are limited in the number of operations that can be performed. These considerations have led to the design of a hybrid system that will combine the best attributes of digital and optical image/feature extraction processing.

During the past seven or eight years, ETL has investigated the use of Optical Power Spectrum Analysis (OPSA) to determine applications for extracting data from aerial photography [1-3]. Typically, in an OPSA system a collimated beam of coherent light limited by a circular aperture is projected through a photographic transparency. The Fourier Transform power spectrum of the transparency object function can be detected in the back focal plane of a transform lens. In a manner exactly analogous to electrical filtering, low power, band pass and high pass optical filters can be placed in the transform plane to pass the desired spatial frequencies. More complicated filters such as differentiating filters can also be used. A second lens can be used to re-transform the light emerging from the filter plane to produce a filtered image. Alternatively, a lens can be placed directly behind the filter to collect the emerging light and focus it on a detector. A variant of this second method is used in the Recording Optical Spectrum Analyzer (ROSA) built by Recognition Systems, Inc. [4]. In this system, a segmented detector consisting of 32 wedges and 32 semicircles is placed in the back focal plane of the transform lens. The detector rings provide frequency information and the wedges provide directional information. The basic ROSA system was modified by ETL to provide computer controlled translation of an aerial photograph. However, the typical sampling aperture is 0.25 inch and an 8- x 8-inch image thus requires 1024 samples. Even with automated translation of the film stage, several hours are required for the repeated sequence of driving the stage to a new location, waiting for vibrations to subside and then moving to the adjacent location. In order to speed up this operation, a prototype system was built that scans a collimated telecentric beam across a photograph. Off-axis parabolic mirrors were used to collimate the beam and Fourier transform the scanned image onto an RSI segmented detector. A production model based on the prototype was built for ETL by Eastman Kodak and delivered in January 1980. After completion of tests, the equipment will be delivered to the Defense Mapping Agency for operational use. Using this equipment, aerial photographs can be rapidly scanned and cloud covered areas rapidly

delineated. Also, the equipment will be used to predict the suitability of conjugate stereo imagery for use in electronic cross-correlation equipment. This equipment is used to generate topographic data from aerial photography.

The fixed geometry of the segmented detector severely constrains the flexibility of an optical processor. An alternative approach to coherent optical processing has been to write spatial filters onto a spatial light modulator (SLM) located in the frequency plane of the filtering system. Iwasa [5] demonstrated such a system using a laser scanner to write filter patterns onto a PROM spatial light modulator. This system used another spatial light modulator for the input object plane. This SLM is useful in three ways:

- eliminates need for liquid gate for input film
- base line subtraction of object function to reduce the intensity of the d-c spot in the frequency plane
- zoom magnification can be removed from the coherent optical train.

This two SLM system was selected as the design basis for the optical subsystem of the hybrid optical/digital image processor.

In order to add a digital processing capability a solid state CC TV camera records the filtered image which is then digitized and stored in the refresh memory of a video processor. The operator can then manipulate the filtered image using the gray scale and color remapping capabilities of the video processor as well as the digital processing capabilities of the mini-computer. The operator can then try new optical filters and iteratively develop optimum methods of detecting patterns. The goal of this research is to develop automated feature extraction algorithms which will minimize the need for human intervention.

#### PCOP optical system

This section presents the optical design concepts and details of the ETL Hybrid Image Processor.

The optical system of the ETL Hybrid Image Processor is called the PROM (Pockels Readout Optical Modulator) Coherent Optical Processor (PCOP). This system will be used to enhance an image transparency through both intensity transfer function manipulation and Fourier plane filtering. The output product is then presented to the digital processing/display system for operator evaluation.

#### Image processing concepts

Optical Image Processing is generally implemented with two basic types of operations: manipulation of the image grey levels (i.e., histogram modification) which is designed to improve detail contrast and recognition; and spatial operations designed to filter, compare, enhance or modify the input image. The spatial operations are performed through Fourier transformation or its image plane counterpart, correlation.

Much recent work has focused on one-dimensional manipulations of imagery and data utilizing acousto-optic modulators. This system, however, is a two-dimensional image processor and has been designed to perform the required operations within the limits imposed by a spatial light modulator.

Figure 1 illustrates the general optical processing concept on which the PCOP is founded. It is basically a Fourier image processor with the option of producing either a reconstructed filtered image or some form of correlation depending on the type of filter used. Both the incoherent input imaging system and coherent Fourier filtering system were designed to optimize the PROM's performance. Processing operations at the first PROM will include contrast enhancement and coherent noise suppression. Fourier filtering at the second PROM will be performed in order to investigate the formation of algorithms for automatic image feature extraction.

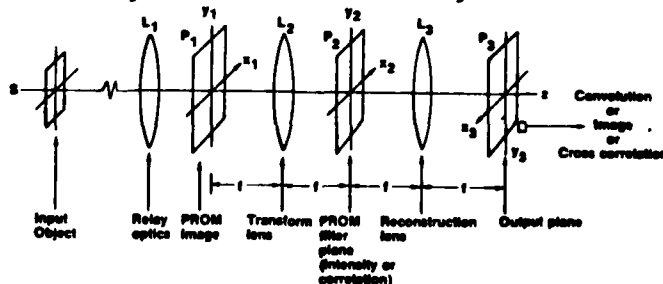


Figure 1. PROM Coherent optical processor general schematic

### PROM operation and characteristics

The PROM is a single  $\text{Bi}_{12}\text{SiO}_{20}$  crystal which is optically polished, covered with an insulator and then coated with transparent electrodes in order to maintain a voltage across the crystal.

The crystal is photo conductive when exposed to blue light. If an image is cast on a PROM in blue light, the image will be stored as a spatially varying potential distribution. Figure 2 illustrates the voltage across the insulating layers and the crystal at various phases of the PROM cycle. This spatially varying potential produces a pattern of birefringence in the crystal, through the Pockels effect, which is related to the original optical image of the PROM. The "birefringent image" can be read out by means of a polarized light beam. If the readout beam is in the red region of the spectrum, image decay due to photo conductivity is minimized.

In the conventional method of PROM readout, the readout beam has a linear state of polarization. The PROM is oriented with its axes of birefringence oriented at  $45^\circ$  to the incoming plane of polarization. The birefringence, which is created by a stored charge image via the Pockels effect, results in an elliptical state of polarization at the output of the PROM. The elliptical state of polarization results in an intensity modulation upon passage through an analyzer. The intensity modulation is functionally related to the original image on the PROM.\*

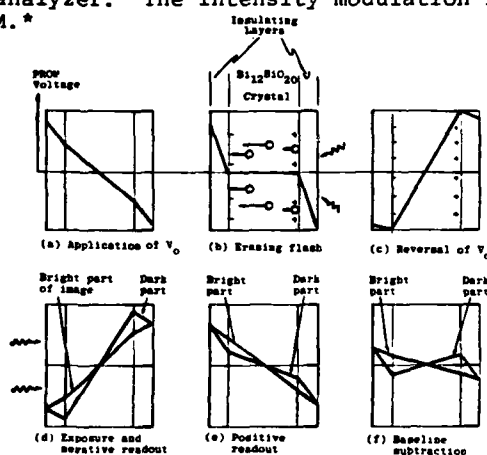


Figure 2. PROM operation  
The basic steps and voltage cycle for PROM operation

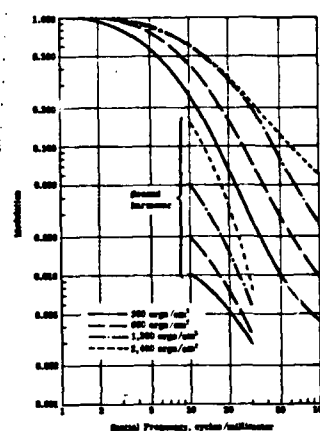


Figure 3. PROM MTF for various exposures measured by diffraction techniques.

### Design goals and system operations

The ultimate goal of this program is to produce a fully interactive Fourier Processor using PROM spatial light modulators. In order to effect this goal, the PCOP optical system is designed to match the spatial frequency range of the input imagery to the modulation transfer function of the PROM. Typical PROM MTF's are shown in Figure 3. In pursuit of this goal, lens  $L_1$  in the general PCOP schematic of Figure 1 was specified to be a zoom optical system operating over a magnification range of 1:1 to 1:4. This insures that the spatial frequency content of areas of interest on the input imagery can be scaled to fall within the region of appreciable PROM response. The image PROM can now be used as the input to a conventional coherent Fourier processor, with lens  $L_2$  as the Fourier transform lens. Image PROM Baseline Subtraction [6] can be used to adjust the image intensity and suppress the D.C. in the Fourier Transform. A Fourier plane filter, written on the Filter PROM by a laser scanner, will effect the desired filtering operation. The image is then reconstructed onto a CID sensor or film (option) for display. Interactive feedback is facilitated for image/filter optimization. The integrated transform is also sensed and interpreted for further analysis by the control electronic system.

The PROM is the key to the PCOP functioning in a real-time, interactive manner. Figure 4, which outlines the System Analysis Tasks in the program, shows that the following questions had to be addressed in order to design the system to capitalize on the PROM's characteristics.

\* A more detailed description of the properties of the PROM and an extensive bibliography can be found in reference 6.





The problems inherent in the K-mirror approach forced investigation of the possibility of rotating the filter PROM. The following Jones Matrix calculation demonstrates that the inclusion of two properly oriented  $\lambda/4$  plates between the customary polarizer-analyzer pair results in an output intensity that only depends upon the PROM's anisotropic phase retardance,  $\delta$ , and not on its orientation.

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = 2\sqrt{\frac{1}{2}} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} e^{-i\pi/4} & 0 \\ 0 & e^{i\pi/4} \end{bmatrix} \begin{bmatrix} \cos^2\theta e^{i\delta/2} + \sin^2\theta e^{-i\delta/2} & 2i \cos\theta \sin\theta \sin\delta/2 \\ 2i \cos\theta \sin\theta \sin\delta/2 & \cos^2\theta e^{-i\delta/2} + \sin^2\theta e^{i\delta/2} \end{bmatrix} \begin{bmatrix} e^{i\pi/2} \\ 1 \end{bmatrix}$$

Electric Field Vector      Analyzer  $\lambda/4$  plate      PROM @ Angle  $\theta$       Polarizer &  $\lambda/4$  Plate

The output intensity is given by

$$I = E_x E_x^* + E_y E_y^* = \frac{\sin^2\delta/2}{2} [\cos^2 2\theta + \sin^2 2\theta + \cos^2 2\theta + \sin^2 2\theta] = \sin^2\delta/2$$

independent of  $\theta$ .

Figure 6 compares the conventional and rotating PROM readout modes. Experiments were performed which demonstrated maintenance of image quality and throughput intensity (to within + 5%) as the test PROM was rotated through  $180^\circ$ . The rotating filter PROM concept avoids the problem of image rotation, and is attractive because of its relative electromechanical simplicity. However, the fact that the PROM has a wedge angle (to avoid coherent readout problems) introduces a wobble of the reconstructed image about the optical axis, which can be corrected by insertion of a compensating wedge rotating with the PROM.

#### PROM readout: Reflection versus transmissions

A PROM may be read out in either reflection or transmission. Readout in reflection appears attractive for two reasons: i.e., 1) Cancellation of the crystal optical activity and 2) Doubling of the effective interaction length in the crystal. While these advantages made reflection the preferred readout mode for early PROM's, recent developments have changed this. The desire to produce more sensitive PROM's has led to thinner PROM crystals, and a consequent difficulty in maintaining surface flatness. The polishing process produces excellent optical surfaces, but the overall crystal figure can be roughly described as a zero power astigmatic meniscus lens. This leads in general to an excellent transmitted wavefront, but a highly aberrated wavefront on reflection. Figure 7 shows interferograms for reflection and transmission readout of the PCOP filter PROM. Analysis of these two interferograms shows a  $.2\lambda$  rms wavefront error for transmission readout and a  $.5\lambda$  error for reflection readout.

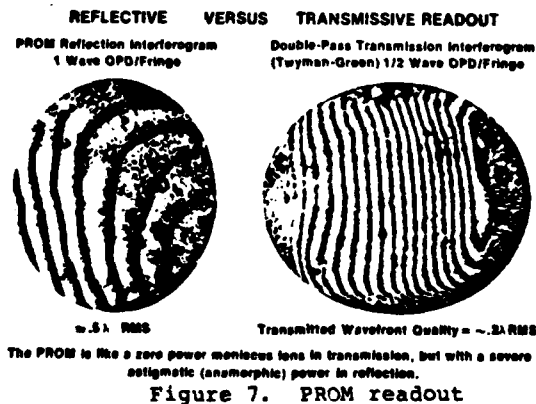


Figure 7. PROM readout

### One PROM and two PROM system options

A primary requirement of the PCOP was the provision of the capability to bypass the image PROM and transform the input image directly. The transform scale change, which was effected in the two PROM system by conjugate changes in the imaging system, is accomplished here by allowing the input transparency to be moved in the focusing transform beam.

A schematic of the optical system shown in Figure 8 shows the PCOP as it is now fashioned. This optical layout will be followed in describing the detailed design.

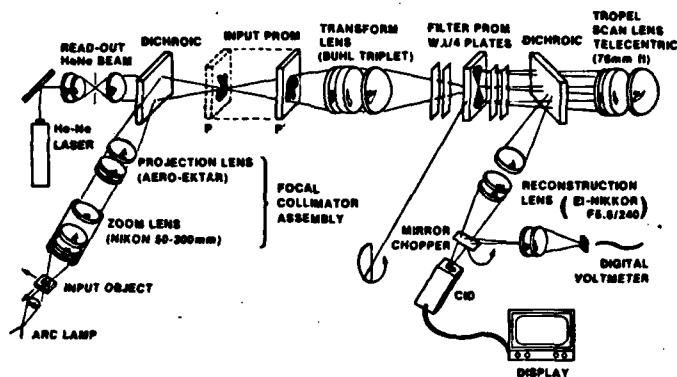


Figure 8. PROM coherent optical processor schematic

### Detailed design

#### Imaging system

This lens system was required to produce an image on the PROM with virtually no degradation at 1:4 conjugate range over a 25 mm image field. The zoom-focal collimator arrangement was defined and found acceptable by its performance of 150 cycles/mm over the field and <25 microns image movement over the full zoom range.

#### Transform-reconstruction system

The major optical engineering and analysis functions performed are illustrated in Figure 9. They were: A) Transform lens analysis - doublet versus triplet. The triplet had flatter field and diffraction limited performance over a larger range of object locations. B) The PCOP has a minimum number of surfaces and no hard apertures. Limiting aperture is the PROM filter. C) Image conjugates were selected for reconstruction compatible with CID sensor, i.e., 1.75:1. D) A coherent imaging experiment verified system performance to the coherent cut-off. E) An incoherent wavefront analysis showed effects of distortions on the phase function, and clearly showed transmission to be the desired PROM read-out mode.

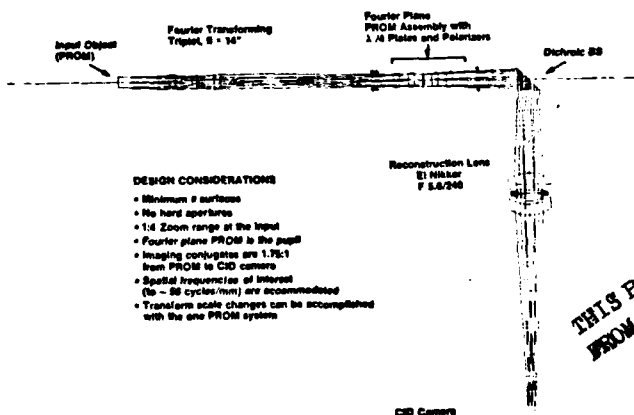


Figure 9. PROM coherent optical processor optical system analysis

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### Dichroic beamsplitter analysis and scan lens considerations

The initial PCOP concept assumed filter PROM readout in reflection. For transmission readout mode, a dichroic beamsplitter is required between the PLS and the filter PROM. An analysis of the mechanical constraints and aberrations introduced by this beamsplitter was performed. As a result, a longer focal length telecentric scan lens is being procured. The aberrations introduced by a plane parallel beamsplitter are minimal (i.e., encircled energy within 20  $\mu\text{m}$  spot is reduced from 84% to 74.5%), and full aberration correction is achieved by a 12-minute wedge on the beamsplitter.

### System image quality and operation

System image quality is summarized along the bottom axis of Figure 4. On the left are displayed representative incoherent MTF's for the zoom-focal collimator lens assembly and the image PROM. It is clear that the effect of the lens on the imagery is minimal and virtually undetectable when the PROM image is used as the input to the coherent processor. The coherent system MTF is classically 1.0 out to the cut-off frequency of  $\approx 50$  cycles/mm imposed by the Fourier plane PROM. This cut-off was verified experimentally; however, the PROM introduced phase distortions which created transient and spurious effects on the imagery. The PROM's effect on the wavefront at the Fourier plane was found to change the output resolution as the input image was rotated, demonstrating localized quality changes on the PROM surface. An incoherent wavefront analysis of the transform-reconstruction system showed the adverse effect of the PROM ( $.2\lambda$  rms) in transmission and its greater effect ( $.5\lambda$  rms) in reflection. This analysis resulted in the point spread functions of Figure 10.

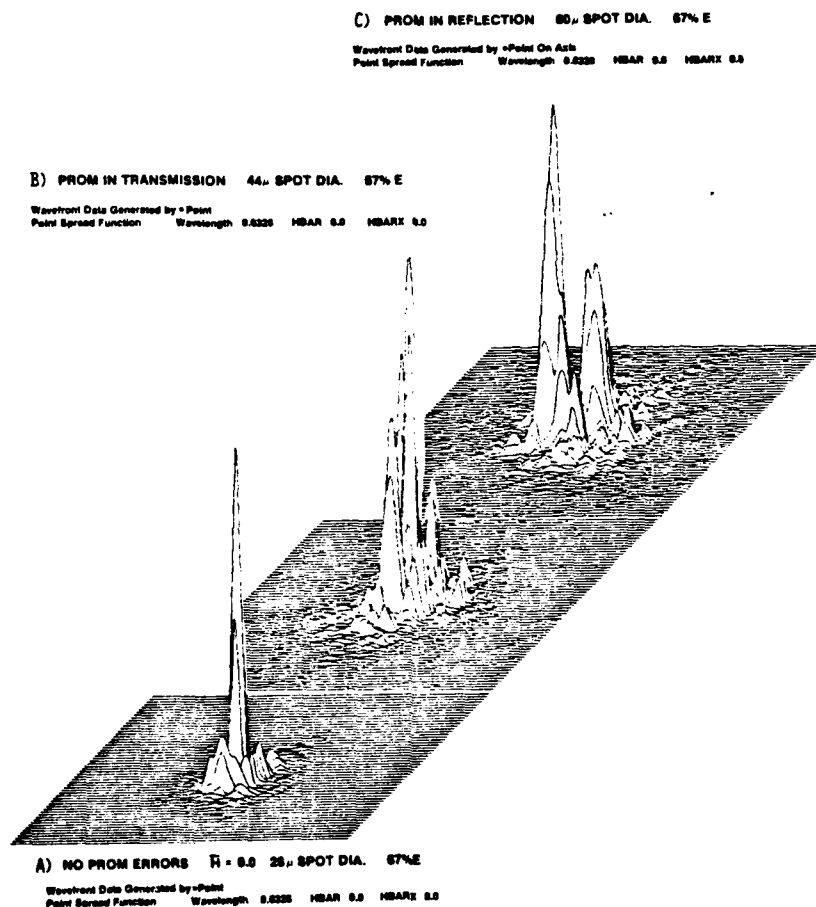


Figure 10. Point spread functions for the PCOP transform - reconstruction lens system from incoherent wavefront analysis, for the on-axis condition

A coherent imaging experiment, using the Filter PROM in transmission, showed that the wedge on the PROM created coherent noise in the outer third of the image with a modulation such that noise contrast was  $\approx 2.1$ . The analysis further showed that the 40-minute PROM wedge angle necessary to remove this secondary interference from the reconstructed image will produce no significant aberration effect on the image. To eliminate the resulting image wobble, a compensating wedge has been designed to rotate with the filter PROM.

Both the one and two PROM systems are designed to operate with interactive control at the stages where an operation is performed on the image. The one PROM system provides limited image conjugate/Fourier scale transformation.

In summary, the PCOP response exceeded that which is typically desired in an electro-optic system (i.e., 40% response at sensor cut-off) by coupling the minimal effects on PROM MTF imposed by the optical system with the scale change from input PROM to output CID image. A significantly higher response is achieved for the one PROM system and increased quality may be achieved with a higher resolution detector, e.g., film.

#### PROM laser scanner

Key constraints in the overall design of the PROM Laser Scanner (PLS) include raster size, number of pixels, bits per pixel, raster writing speed and geometric accuracy. The raster size is determined from the useful area of the PROM crystal. For a 13-millimeter square raster, a minimum resolution of about 500 x 500 pixels was selected. This was a compromise between the conflicting requirements of image quality and raster writing speed. The corresponding pixel diameter is 25 micrometers. The design goal was for a raster writing speed of less than one second.

It is anticipated that spatial filters will frequently be binary, thus requiring only one bit per pixel. However, even packing 16 pixels per word, required buffer space for the filter exceeds the available computer memory space. However, further compaction can be achieved by considering the nature of the typical binary filter. A binary filter will usually be a two-dimensional low pass, band pass or high pass filter with a limited number of black-white transitions on a given scan line. Therefore, the video can be stored in a run-length-code format with only the number of sequential ones or zeros stored in memory. For example, nine transitions per line would require only 5000 words of memory with a 16 bit run-length-code for each segment. From these considerations, the PLS was designed to have two modes of operations: six-bit gray shade and one-bit binary.

Focal Length	76.5 mm
f/no.	5.2
Angular Coverage	$\pm 20^\circ$ telecentric
Spot Size	7 $\mu\text{m}$
Scan Length	52 mm
Operating Wavelength	441.6 nm

Table 1. Scan lens specifications

1. 512 x 640 x 12 bit memory stores television image.
2. Zoom magnification ratio: integer steps from 1:1 to 16:1.
3. Continuous left to right, up and down scrolling capability.
4. Look up table provides gray shade and color remapping capability.
5. Vector graphic and alphanumeric capability.
6. Block read/write commands from host computer.
7. Random pixel read/write commands from host computer.

Table 2. Video processor performance characteristics

The original design of the PLS assumed the PROM would be operated in reflection mode. The recently completed design study for the PCOP concluded that the PROM should be operated in transmission mode with a beam splitter placed between the scanner and the scan lens as shown in Figure 8. A scan lens that meets the requirements of the PLS with transmission mode read-out was identified. Its specifications are shown in Table 1. For a half inch raster, only a 15-degree scan is required. When larger area PROMs become available in the future, this lens will permit increasing the raster size.

Acousto-optical deflectors and polygon scanners were considered as candidates for the fast axis scan. The acousto-optical deflector has more than adequate scan speed, but in order to achieve uniform illumination across the image, the nominal 80 percent efficiency of an acousto-optical modulator is reduced to about five percent. The decision was made to use a 16 facet polygon scanner. This scanner will deflect an incident laser beam through a total angle of 45 degrees resulting in a 33 percent duty cycle (when the polygon mirror scanner was originally purchased, a different scan lens with a scan angle of  $\pm 16.5$  degrees and a corresponding 55 percent duty cycle was selected for use in the system).

A General Scanning 300 PDT galvanometer with temperature control was selected to control the slow axis scan. Error analysis indicates that the on-line computer will have to be used to correct non-linearities in the scan.

### Optical system

The optical configuration of the PROM Laser Scanner is shown in Figure 11. The laser used for the scanner is a 15 mw HeCd laser operating at 441.6 nm. An acousto-optical modulator is used to modulate the laser beam which is then expanded and collimated. The lenses  $L_1$  and  $L_2$  act as a telescope to image the galvanometer mirror surface onto polygon scanner mirror surface. The entrance pupil of the flat field scan lens is 25 mm in front of the physical lens. This lens is positioned such that the entrance pupil coincides with the polygon mirror surface. The PROM spatial light modulator is positioned in the back focal plane of the scan lens.

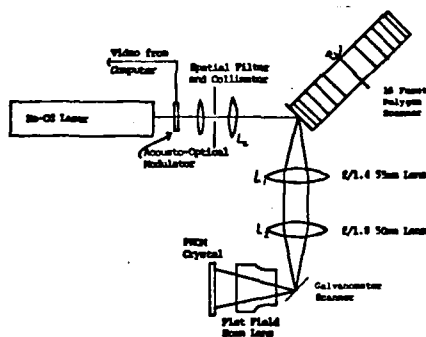


Figure 11. PLS optical layout

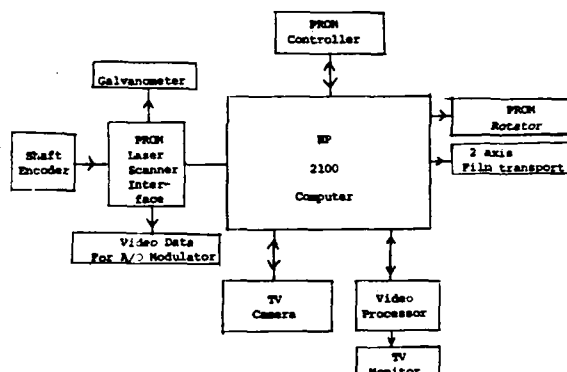


Figure 12. Digital control block diagram

### Digital control/data processing system

A block diagram of the HP computer and interfaces required to control the Hybrid Optical/Digital Image Processor is shown in Figure 12.

The PROM Laser Scanner interface was designed to have a scanner motor run at constant speed with shaft encoder signals used to control the timing of the computer interface. This approach requires that the computer will always be able to respond within the required time interval. Therefore, the motor speed must not exceed the rate at which data can be transferred to the interface. The shaft encoder provides a zero reference signal plus an 8192 count per revolution signal. These signals are used to generate the start of scan signal and pixel strobe signals. The video data are strobed 12 bits at a time alternately into parallel input shift registers. In the binary mode, data is shifted out serially to form the video signal while in the six-bit gray shade mode, the low order six bits are strobed from the parallel output of the shift register into a D/A converter. Subsequently the high-order six bits are strobed to the D/A converter.

Computer programs have been written to generate wedge filters, compact the data into run-length-code format and control the laser scanner.

A GE 2500 CID camera was selected to digitize the filtered image. This camera is equipped with an eight-bit parallel digital output. The data rate, however, is 4.5 Mhz, considerably in excess of the I/O capacity of the HP computer. An interface built by ETL for use with another solid state camera will be modified for use with this camera. The interface "grabs" every nth pixel where n is an integer that is not a factor of the total number of pixels in a frame. After n frames, all pixels will have been read into the computer. The computer will store the video in a Lexidata 3400 video processor. The data arrives from the interfaces in a scrambled order and must be unscrambled by the computer.

The Lexidata video processor uses a manufacturer supplied interface to communicate with the HP 2108 computer. The processor contains a 512 x 640 x 12 bit refresh memory that generates the RGB signals for a color television monitor. A look up table provides gray shade color remapping capabilities. Table 2 describes the important performance characteristics.

Hewlett-Packard micro-circuit interface cards will be used to interface the film translation stage, PROM rotator, PROM control box and Fluke voltmeter. Consideration is being given to using a microprocessor to control the film drives and PROM rotator. The microprocessor would also use a micro-circuit interface card for communication with the HP computer.

#### Applications

The video processor can store four filtered images from the CID camera. The operator will be able to command the processor to display the images in sequence and thereby emphasize the effects of different optical filters. Pseudo-color can be used to emphasize the subtle differences produced by varying the spatial filter. The operator can then try new optical filters and iteratively develop optimum methods of detecting patterns.

A large digital pattern recognition program called FACEL which was developed by Recognition System Incorporated is currently being used with data from our Recording Optical Spectrum Analyzer. It is anticipated that elements of FACEL will be useful in the Hybrid Optical/Digital Image Processor.

It is anticipated that this hybrid processor will provide a highly flexible system for investigating methods of combining optical and digital processing to develop automated feature extraction algorithms that will minimize the need for human intervention.

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